ALTERNATIVE FORMATION MECHANISMS FOR TERRESTRIAL CRATER CHAINS. S. G. Love[1], W. F. Bottke[2], and D. C. Richardson[3]. [1]Seismological Laboratory 252-21, Caltech, Pasadena, CA 91125. [2]Div. of Geological and Planetary Sci. 170-25, Caltech, Pasadena, CA 91125. [3]Box 351580, Dep't. of Astronomy, Univ. of Washington, Seattle, WA 98195.

In an accompanying LPSC abstract [1], we investigate whether crater chains analogous to those seen on Ganymede and Callisto [2] might be formed on the Earth and Moon by the tidal breakup of "rubble-pile" asteroids or comets. In our treatment, these objects are disrupted during close approaches to either the Earth or the Moon, with the resulting fragment trains proceeding directly to collide with the other. This mechanism can account for 1-2 crater chains on the Moon (consistent with observations [3]), but none on the Earth [1] in contrast to recent suggestions [4, 5]. This disagreement raises the question of whether terrestrial crater chains might form by other processes. Here we briefly examine four possible alternative mechanisms for making primary crater chains on Earth. (We neglect chains of secondary craters created by ejecta from larger impacts.)

SCENARIO 1 The first scenario works for asteroids or comets with very low v_∞ (approach velocity before acceleration by the Earth). Although they are scarce [6], these bodies may (at least in principle) be captured by the Earth through three-body interactions with the Earth and Sun [7]. An asteroid or comet thus captured could suffer tidal disruption at one perigee and return to make a crater chain at the next, analogous to the case of comet Shoemaker-Levy 9 (SL-9) at Jupiter. This process is not effective at making crater chains on Earth. Solar perturbations to a captured body's orbit are strongest near the boundary of the Earth's sphere of influence, so that the interloper's apogee tends to remain at that distance [7]. The round-trip flight time from a low perigee to the edge of the sphere of influence and back is about 3 months. Because the length of a tidal disruption fragment train grows steadily with time after breakup [1, 8], the flight time is directly related to the size of the resulting crater chain. The two crater chains we recognize on the Moon are ~50 and ~250 km long [3]; they were formed after flight times of no more than 3 days, and more likely (for typical encounter velocities [6]) ~0.5 days, from periapse and breakup at Earth to impact on the Moon. Three-month flight times thus lead to crater chains ~100 x longer than the lunar ones. This is much larger than the proposed terrestrial chains (~50 and ~700 km). Also, such long chains might be distorted by Earth rotation, like the SL-9 impact sites on Jupiter.

SCENARIO 2 The second scenario builds upon the first. A captured body might possibly pass near the Moon, lowering its apogee to the lunar distance and shortening its orbit period to ~10 days. This is perhaps short enough to keep the spread of debris from one perigee to the next within the limits of the proposed crater chains. Lowering the apogee from the edge of the sphere of influence to the Moon's orbit radius requires a Δv of ~1.5 km/s. The Moon can supply such velocities, but only if the interloper passes within a few lunar radii. The Moon's cross-section for such encounters is thus comparable to its cross-section for impacts in general, and its chance to make crater chains on the Earth via this mechanism is not much larger than the rate at which it accumulates crater chains itself. As we have shown, that rate is too low to produce terrestrial crater chains in observable geologic history [1].

SCENARIO 3 The third scenario, tidal breakup of an asteroid or comet during a close flyby of another planet or the Sun with the resulting fragment chain proceeding to strike the Earth, can be dismissed for three reasons. First, no crater chains have been found on Mercury, Venus, or Mars [2], all of which are targets for this mechanism with cross-sections comparable to the Earth's. Second, the Moon is a large target in the Earth's sky, but the Earth has produced only 1-2 crater chains on it in 3.8 billion years [1]; the formation rate for crater chains amongst the inner planets, whose angular areas as seen from one another are orders of magnitude smaller, must be correspondingly lower. Last, flight times between the inner planets are ~0.5 year. Following the argument given above, such long flight times produce crater chains larger than the lunar ones by a factor of ~200, much longer than the proposed terrestrial crater chains.

SCENARIO 4 A dramatic fourth scenario involves an asteroid or comet which makes a grazing passage through the Earth's atmosphere. Ram pressure [9] and tides cooperate during aerobraking to disrupt the interloper, while air drag absorbs enough kinetic energy to capture it into a short period orbit [10]. The fragment train might strike the Earth at a subsequent perigee, making a chain of craters. (Atmospheric or tidal breakup immediately before impact yields crater separations much smaller than observed in crater chains [11].) We have tested this scenario by adapting and improving a computer model originally developed for the atmospheric entry of cosmic dust particles [12] to treat km-sized meteoroids. The model assumes a unit drag coefficient and neglects shape change of the spherical projectile in the atmosphere. The trajectory analysis includes the Earth's gravity and curvature and employs the accurate atmospheric density profile (from sea level to 200 km) tabulated in the *United States Standard Atmosphere* of 1976.

Our calculations suggest that there is a very narrow window of flight angles (corresponding to perhaps 1 in every 1000 objects that hit the Earth) within which a 1-km diameter body might be captured during an aeropass. The capture window is plotted as a function of v_∞ in Fig. 1. A body destined for capture enters the atmosphere at a shallow angle and descends to a minimum ~10 km altitude. At that height the velocity is too low for escape but still exceeds circular orbit speed, so the interloper ascends, exits the atmosphere, and completes almost a full orbit (almost any apogee is possible) before reentry. Aerobraking continues until the object strikes the ground.

This mechanism seems able to make crater chains of the right extent, but it has a different problem. In this scenario, the interloper fragments fly almost horizontally when they hit the ground, and would form distinctive elongated craters upon impact. Steeper impact angles (and rounder craters) are possible if the projectiles lose enough forward velocity during aerobraking to effectively "fall" from perigee. Falling from 10 km altitude implies vertical speeds of ~500 m/s and total velocities not much above 1 km/s. This is fast enough to make a big hole, but much slower than typical impacts on the Earth. The resulting craters might thus lack some of the physical hallmarks (e.g., impact melt, shatter cones, shock lamellae) of true hypervelocity impacts, and might be difficult to distinguish from secondaries.

SUMMARY We have shown elsewhere [1] that terrestrial crater chains probably do not form via tidal breakup of weak asteroids and comets by the Moon. Breakup by the Sun or by another planet is even more unlikely. Breakup of a temporarily captured object followed by impact on a subsequent orbit has been demonstrated by SL-9 at Jupiter, but the SL-9 fragments struck at widely separated points on a line of constant latitude rather than making a classical crater chain. We believe that the analogous process at Earth would produce similar results. Using the Moon to lower the apogee of a captured object so that it produces a more compact chain is conceivable but unlikely within observable geologic history. Finally, aerobraking can probably disrupt 1-km asteroids while capturing them into short-period orbits, but the resulting craters would show strong elongation and/or signs of an unusually slow impact.

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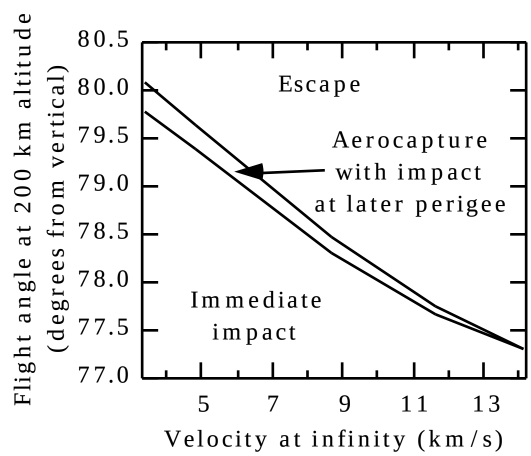

FIGURE 1. Flight angles and velocities for aerocapture by the Earth of 1 km diameter silicate bodies. Minimum altitude in the capture aeropass is ~10 km. Aerocapture may occur for 1 out of every ~1000 objects that hit the Earth.